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AUGER EFFECTS INVOLVING RECOMBINATION CENTRES

P. T. LANDSBERG, D. A. EVANS and C. RHYS-ROBERTS

UNIVERSITY COLLEGE, CARDIFF, GREAT BRITAIN
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It is well known (Shockley and Read, 1952) that the statistics for the recombination of electrons and holes in semiconductors by single-electron processes via localized states leads to a recombination rate per unit volume

$$U = \frac{np - n_i^2}{\tau_p(n+n_1) + \tau_n(p+p_1)} \qquad (1)$$

Here n_1 and p_1 are electron and hole concentrations respectively when the Fermi level is at the trap level. τ_n and τ_p are steady-state lifetimes of the minority carriers in p-type and n-type material respectively. If the four possible Auger effects which involve the localized state are taken into account, one arrives again at (1), except that τ_n and τ_p are replaced by τ_n^* and τ_p^* (Evans and Landsberg, 1963). The interpretation of the τ^*'s as steady-state lifetimes of the minority carriers remains valid. However, the τ^*'s depend now on the carrier concentrations:

$$N/\tau_n^* = T_1^s + T_1 n + T_2 p \qquad (2)$$

$$N/\tau_p^* = T_2^s + T_3 n + T_4 p \qquad (3)$$

T_1^s and T_2^s are mass-action constants for the Shockley-Read processes and the other four T's apply to the Auger effects. N is the concentration of recombination centres.

Some striking experiments on the lifetimes of minority carriers in heavily-doped germanium have been published by Karpova and Kalashnikov (1962). These authors find concentration-dependent lifetimes in samples cut from

ingots (their figs. 1 and 2), and also in samples into which additional copper was introduced by diffusion (their fig. 3). An attempt to fit the relations (2) or (3) to the experimental curves was successful only in the case of the diffused specimens (n-type). This is illustrated in the accompanying graph (fig. 1), in which the discrete points are transferred from Karpova and Kalashnikov's fig. 3, while the solid line was calculated using equation (3), and the concentration $N = 1.5 \times 10^{14}$ cm^{-3}, given by these authors. The best fit obtainable is shown in the figure and corresponds to

$$T_2 = 6.8 \times 10^{-25} \text{ cm}^3 \text{ sec}^{-1} \text{ and } T_3 = 10^{-26} \text{ cm}^6 \text{ sec}^{-1} \quad (4)$$

A variation of $\pm$ 10% from these figures still yields a reasonable fit.

Karpova and Kalashnikov state that the holes are captured into the copper level lying $E_t = 0.26$ eV below the conduction band. This enables one to apply the formula

$$T_3 = \frac{128\,\pi^2 e^4}{\varepsilon^2 m_e^2} \left(\frac{\hbar}{E_G}\right)^3 \frac{E_t}{E_G} \cdot \left(\frac{E_t}{E_G - E_t}\right)^{3/2} \quad (5)$$

(Banch-Bruevich and Gulyaev 1960), where E_G is the energy gap, ε the dielectric constant and m_e the effective electron mass. Using $m_e = 0.22\ m_0$, $\varepsilon = 16$, $E_G = 0.665$ eV, (5) yields $T_3 = 1.36 \times 10^{-27}$ cm^6 sec^{-1}, which is a factor of 7.3 smaller than the empirical value. The formula (5) needs

correcting because of certain overlap integrals which ought to be included, and because of certain approximations made in integrating over electron and hole distributions. The first correction tends to reduce (5) while the second tends to increase it. If one includes only the second correction the theoretical value of T_3 becomes $2.32 \times 10^{-27} cm^6 sec^{-1}$ and is smaller than the empirical one given by (4) only by a factor of 4.3. There is, of course, an additional uncertainty regarding the value of the effective mass one ought to use in (5)

To obtain (5) the centre is regarded as hydrogen-like with an ionisation energy related to the conduction band. If the ionisation energy is related to the valence band, of a different formula is obtained, but it yields only a slightly different value of T_3 for this case.

If one interprets the 0.26 eV level as corresponding to a doubly negatively charged ion before hole capture, one finds from the work of Mashovets (1958) an independent empirical value of $T_2^s = 20 \times 10^{-10}$ cm^3 sec^{-1}. There is, therefore, adequate independent evidence that the order of magnitude of the constants (4) is correct.

This is particularly interesting as it seems to furnish the first empirical estimate of T_3. The reasonable agreement with a theory leading to (5), based on hydrogen-like wave functions makes it desirable to develop this approach further. This will be done in a future communication (Landsberg, Rhys-Roberts and Lal 1963). In this paper the

the corrections to equation (5), which have been mentioned above, are discussed in detail, and the theory of the mass-action constants $T_1 \ldots T_4$ is presented in a unified manner. This theory deals also with the case when recombination or impact ionisation involves an excited state, rather than the ground state, of the recombination centre.

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Fig. 1.